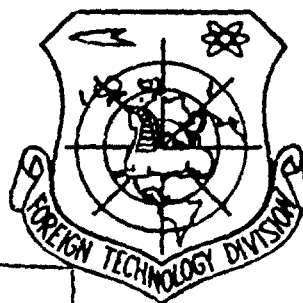# FOREIGN TECHNOLOGY DIVISION

SPECTRAL TRANSPARENCY AND MICROSTRUCTURE OF
ARTIFICIAL FOG

by

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SPECTRAL TRANSPARENCY AND MICROSTRUCTURE OF ARTIFICIAL FOG

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I. Apparatus and Method of Measurement

·This article describes the apparatus, measurement method
and results of experimental studies of the microstructure and
spectral transparency of artificial fog. It is demonstrated
that the data obtained may be used applicably to natural liquid-
droplet clouds and fog.

One of the important problems of studying clouds at present is
the investigation of their optical properties [1]. Of greatest value
in this respect are data on optical properties of clouds obtained in
the infrared spectral range and accompanying simultaneous measurements
of the microstructure. They are extremely necessary for calculating
the radiation regime of clouds and of the entire atmosphere, and for
solving a number of other problems of atmospheric optics. Nevertheless,
for actual clouds and fog these data have until now been very few in
number [2, 3]. Such a situation is easily understood taking into
account the great expense and technical difficulties involved in
carrying out experiments in actual clouds and also the peculiar
nature of the latter (rapid changeability with time and space).

In connection with what has been said of significant interest are studies of the optical and microphysical characteristics of artificial fogs correctly modulated according to the characteristics of natural clouds and fog. In this case the results obtained in a chamber may be transferred after thorough analysis to real clouds and fogs.

The authors have carried out experimental studies of the spectral transparency of artificial clouds in the visible and infrared range and their microstructures with variations of parameters of the latter which encompass those realized in natural clouds and fogs.

Apparatus

All microphysical and spectral measurements were carried out in a chamber of artificial fog with a volume of 15 m^3, the clouds in which were produced by steaming. In a compartment adjoining the chamber were mounted a photometer and an infrared spectrometer IKS-6 for measuring the transparency in the visible and infrared ranges with respect to mutually intersecting (at an angle of about 30°) directions as well as an apparatus for remote control of the instruments located in the chamber. The direction distance was established respectively: between the spectrometer IKS-6 and projector with globar used as a source of radiation — 2.5 m; between photometer with FEU-22 and lens projector with incandescent lamp as the source of radiation — 3.0 m. At the point of intersection of the paths was grouped the apparatus for microphysical measurements. The distance from the chamber wall to the beams at their largest section exceeded one meter. For stable operation of the receiver systems the temperature in the chamber was maintained constant. The stability of radiation of the sources was controlled and was satisfactory.

By means of the photometer it was possible to measure the transparency for four narrow portions of the spectrum with centers about 0.42, 0.68, 0.94 and 1.03 μ and with a width from 20 to 30 mμ. The spectrum intervals were isolated by selecting glass and interference light filters. The spectrometer IKS-6 assures the possibility of obta ing continuous data regarding transmission in the range from 2 to 15 μ

By means of apparatus located within the chamber, simultaneously with measurements of transparency we carried out a determination of the following microphysical characteristics of artificial fog: concentration of droplets, function of distribution of droplets with respect to dimensions and parameters; water content of the fog, the content of small-droplet fraction in fog. For these studies we used a complex of apparatus consisting of continuously operating entrainme separators of haft and drum type developed in the El'brussk Expediti of the USSR Academy of Sciences [4], entrainment separators of curvilinear flow, developed in the SFTI [5] and the guaranteeing registration of small-droplet fraction of artificial fogs clear up to droplet with a diameter of 0.8 μ and optical instruments based on the method of small angles, the idea of which was presented by Shifrin [6] and Sleptsevich [7]. The optical establishments from photographic(on moving film)and photoelectric (on an oscillascope screen) registration of indicatrixes of scattering at small angles were constructed and prepared at the SFTI and made it possible to carry out practically continuous observation of the microstructure of fogs during the proces of optical measurements.

Method of Measurement of Spectral Transparency of Fogs

One of the basic conditions of the experiements carried out by us was the synchronous measurements of spectral transparency and

microphysical characteristics of artificial fog. Strict satisfaction
of this condition was dictated also by the circumstance that from the
moment of creating fog till its complete dispersion there was a
total of 4 − 7 min. In this connection we gave synchronizations of
optical and microphydical measurements the most serious
attention.

Tne temporary nature of artificial fogs also did not permit tne
recording of a signal on the spectrometer in connection with the fact
that measurements were carried out during the course of a single intake
of vapor at one of the following fixed wavelengths: 2.15, 3.7, 6.5,
8.0, 10.0. and 11.8 μ. Simultaneously with this, measurements of
transparency were carried out in the visible range for a parallel
beam and wavelength $\lambda = 0.42$ μ by means of the photometer.

Measurements of transparency using the IKS-6 were carried out with
recording on photo paper on which time marks were made every minute.
According to the signal together with the time mark, evaluation was
made according to the indicator of the photometer. In the future when
processing results it was assumed that suoh data were obtained simul-
taneously and refer to the same fog. Suoh an assumption is justified
since the nonsimultaneous nature of measurements did not exceed 1 − 2
sec.

The total error when determining the signal from the source is
totaled from the errors due to the receiving apparatus, instability
of the radiation source and instability of the diffusing medium. The
performed analysis of the enumerated errors indioated that the
maximum error in determining the magnitude of the signal for measure-
ments in the infrared range of the speotrum amounts to 5 − 10% if the
transparency of the fog varies over the range 0.4 − 0.7. With

measurements in a more dense fog the measurement error increases and may reach 30% and more. In order that in such cases the accuracy of determining the coefficient of attenuation is significantly increased, several subsequent calculations were made, the use of which reduced the mean square error several times.

With measurements in the visible spectral range the maximum absolute error in determining optical density did not exceed 0.05.

Method of Microphysical Measurements

Simultaneously with the notation of time on the photorecord of the spectrometer, traps for gathering fog droplets were switched on by means of a control panel. An automatic device permitted taking samples each second; the number of samples per measurement varied from 3 to 5 depending on the fog density. The period of plate exposure in the trap could also be varied over wide ranges — from 0.04 sec to 0.6 sec. The rate of aerosol flow through the trap tube could be varied from 10 m/sec to 27 m/sec. A large number of samples were taken from a flow whose velocity equaled 15 m/sec.

Each of the samples taken was microphotographed under a MBI-1 microscope 5 or 6 times; microphotographs were processed by means of a commutation comb and tabulators with a total magnification equal to 2000[8]. In order to obtain parameters of distribution, histograms were processed graphically and in a number of cases by a computational method. During the graphical method in order to hasten the process of treating samples a selection of scales for the parameter μ was used [9] which varied from 0 to 8. With the computational method the parameters of distribution and microcharacteristics of the fog were determined from the following formulas:

$$q = \frac{\bar{\pi}}{6} \sum_i n_i d_i^3 \; ; \quad d_2 = \sqrt[2]{\frac{\Sigma n_i d_i^2}{\Sigma n_i}} \; ; \quad d_3 = \sqrt[3]{\frac{\Sigma n_i d_i^3}{\Sigma n_i}} \; ,$$

where q is the water content of the fog; d_2 the mean square diameter; d_3 the mean cubic diameter; n_i the concentration of droplets the i-th interval obtained taking into account the coefficient of capture; d_i the average value of diameter of the i-th interval. Comparison of data obtained by processing the samples by two methods indicated their good coincidence.

Errors of the microphotographic method were analyzed by us earlier [10]. As follows from this previous work the errors in measurement of water content may reach 15%, the parameter of halfwidth μ — 1-2 units, particle concentration — 7-10% depending on the quantity of droplets counted. In measurements described in the present article the number of droplets in the sample varied from 200 to 3000 with an average of 600.

In this connection the total error of microstructure measurements did not exceed 20-25%. In individual cases special measures of precaution were taken, as a result of which the error in measurements may be reduced to 10-15% [10].

For the purpose of obtaining data regarding the small-droplet fraction of fog simultaneously with the taking of a sample of a continuous trap not exceeding droplets with a diameter smaller than 3 μ, the microstructure of the fog was studied using a trap of curvilinear flow. The sample on the partition plate of the latter was worked both with the ordinary microphotographic method as well as with the express method proposed in [5]. The graduated curve required for utilizing the express method is determined by the processing of the microphotographic partition plate; such type of graduating of the trap of curvilinear flow yields a sufficiently precise and

-6-

reliable experimental determination of the parameters of the distribution function. The minimum droplet diameter taken by the trap proved equal to 0.8 μ.

A portion of measurements of spectral transparency of fogs was accompanied by the determination of their microstructure using photoelectric and photographic measurements of the refractive index using the method of small angles. A significant difference of these devices from those described in the literature [1] is the fact that they utilize practically continuous determination of the refractive index in small angles and consequently follow the microstructure of the fog.

Distribution functions calculated according to formulas proposed by Sleptsevich [7] and Shifrin [12] were compared with the microstructure determined by simultaneous continuous flow traps. Also several determinations were made of the parameters of distribution by the Mikirov method [13]. Comparison of results obtained by various methods indicate their satisfactory coincidence.

II. Results of Measurement of Spectral Transparency and Microstructure of Artificial Fog

As was pointed out in [1], the measurements of microstructure of fogs were carried out simultaneously with continuous flow traps and traps of curvilinear flow. In all 200 tests were made with the continuous flow traps in the chamber, the average number of droplets in each sample being 600. Processing of the samples indicated that with a flow velocity in the trap tube of 15 m/sec the minimum diameter of taken droplets in the center of the plate equaled 3.0 μ, as distinguished from the value of $d_{min} = 4\mu$ obtained in work by the El'brussk Expedition of the USSR Academy of Sciences [8]. The

concentration of droplets, according to data from the continuous flow trap, varied from 900 cm^{-3} at the start of the experiment to 5-8 cm^{-3} at its end; the water content of the artificial fog calculated from results of processing the samples varied over the range from 0.6 g/m^3 to 0.003 g/m^3. The mean square diameters of the droplets in the samples d_2 varied from fog to fog over wide limits from 7.5 μ to 22.2 μ; more than half of all the samples had a d_2 from 11 μ to 15 μ.

Processing of sample microphotographs obtained with continuous flow traps indicated that in 110 samples the droplet dimensions satisfy γ distribution. In most cases in the probe containing no less than 400 droplets the parameter of the half-width distribution μ and the mean-square diameter d_2 obtained in our experiments and indirectly realized in actual conditions require the application of the data obtained by us to actual liquid-droplet clouds and fogs.

For 32 tests the distribution of drops by size had the parameter $\mu = 2$. The average value of the parameter μ was 2.48, which is close to the average measured by Khrgian and Mazin in natural clouds [14].

The large range of halfwidth μ and mean-square diameter d_2 that we obtained in our experiments and that overlap what is realizeable in natural conditions allow us to apply our data to natural liquid-drop clouds and fogs.

As was noted above, distributions obtained by means of the continuous flow traps appear exaggerated due to the smallness of the capture coefficient for droplets with a diameter smaller than 3 μ, which makes analysis of fine-droplet fractions impossible. Moreover the continuous method also requires a great expenditure of time on extremely tedious processing of the samples. These disadvantages were overcome to a known degree in the method of aerosol sample intake from a curvilinear flow proposed in [5].

Thirty-seven samples of droplets from an artificial fog ere taken with a curvilinear flow trap simultaneously with a continuous flow trap. Their synchronous character of operation of the two traps was maintained with great accuracy so as to assure the taking of fog samples with little difference in characteristics of microstructure in both cases.

Comparison of data regarding the microstructure of artificial fog obtained simultaneously with a continuous flow trap and a curvilinear-flow trap is shown in Fig. 1. The solid lines indicate histograms obtained by processing data from a continuous flow trap with the introduction of a capture coefficient, the broken lines — histograms obtained with a linear-flow trap with the assumption that the cross-section coefficient of droplets of various dimensions equal unity. All intervals of averaging with the exception of the second equaled 3μ. The second interval Δd equaled 2μ. Inspection of Fig. 1 indicates that for droplets with $d > 3-5 \mu$ the histograms coincide or are very close to one another. From this it may be concluded that for droplets with a diameter greater than 3μ the capture coefficient of the curvilinear-flow trap is actually close to unity.
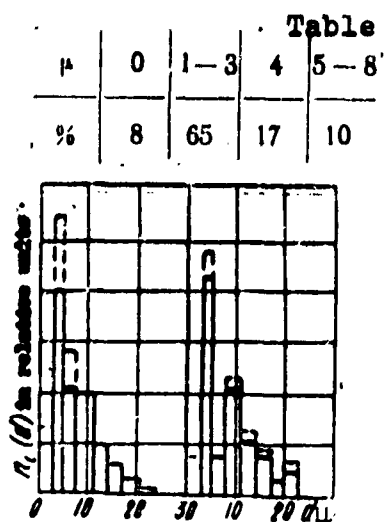
Table

μ	0	1 — 3	4	5 — 8
%	8	65	17	10

Fig. 1

For droplets with a diameter smaller than 3 μ it was assumed that the capture coefficient also did not greatly differ from unity clear up to dimensions of 0.8 − 1 μ. An indirect indication of this situation is found in the fact that on the collection plate the area occupied by precipitative droplets is sharply limited from the side of small droplets, the minumum dimensions of which equal 0.8 − 1 μ. On the remaining portion of the collection plate there were absolutely no precipitated droplets, which indicates either the absence in the fog of droplets with a diameter less than 0.8 − 1 μ or a sharp decrease in the capture coefficient for droplets of such dimensions to zero or rapid vaporization of them into a mixture. It should be noted however that there are no direct indications pointing to the assumptions made due to the absence of absolute methods of analyzing fine-droplet fog fractions.

With an increase in the mean-square droplet diameter in the samples the coincidence of data obtained by means of both traps is worsened. Where for d_2 = 7-10 μ the divergence of values of mean-square diameter obtained by both methods does not exceed 0.1 − 0.3 μ, then for d_2 = 18 − 22 μ this divergence reaches 2μ, whereupon the fine-droplet ranges of distribution coincide sufficiently well and greater divergences are observed in the range of larger particle dimensions. This peculiarity is easily explained by the nonuniform distribution of droplets of various size with respect to the collection plate of the curvilinear-flow trap due to the fact that droplets of larger size run together and are not processed.

The minimum droplet diameter at the collection plate of a curvilinear-flow collector is ∼0.8 μ. It is not possible to determine the precise values of droplet size since the image of droplets of

such size is greatly erroded by the defraction halo. Utilizing a curvilinear-flow 'rap which assures the collection of extremely small droplets it became possible to analyze the fine-droplet fraction of artificial fog. Such analysis indicated that additional maxima of distribution in the range f dimensions 1 — 4 μ are absent. In the range of large droplet dimensions additional maxima are observed for a portion of the distributions.

Let us note yet one more important advantage of curvilinear-flow traps associated with the significantly smaller effort required for processing the collected samples. If the method described in [5] is used it proves possible to determine the distribution parameters without measuring the image size of each droplet. For rapid evaluati of distribution function parameters it is possible also to give up the microphotography of collected samples, determining the number of droplets on a segment of the sample directly by a count within the field of vision of a microscope. We have made such determination of distribution parameters whose results were compared with data obtaine by the ordinary microphotographic method. For distributions, in whic the mean-square droplet diameter does not exceed 10 — 12 μ, the discrepancy between data obtained by the two methods fell between the limits of measurement error. This makes it possible to recommend the method developed for field measurements of distribution function whe. final results must be obtained rather quickly.

The Transparency of Artificial Fog and Its Connection With Microstructure

Simultaneous with the determination of the microstructure of artificial fog, measurements of spectral transparency were made. On the whole more than 50 fogs were studied among which more than 150

measurements were made of spectral transparency accompanied by

measurements of microstructure. In all experiments transparency w is

determined in the range of 0.42 μ and in one of the infrared spectal

ranges with centers at 2.15 μ, 3.7 μ, 6.5 μ, 8.0 μ, 10.0 μ and 11.8 μ.

Measurements of transparency in the range of 0.42 μ and of one of

predetermined spectral ranges were made over the range of the entire

existence of the fog.

The optical density τ of the tested fog was measured in the range

0.1 − 1.5, the attenuation factor $k_{0.42}$, calculated every centimeter

from 2.10^{-4} to 52.10^{-4} cm^{-1}.

According to data on the microstructure measurements for the

fogs tested the geometric cross sections of the droplets in units of

volume S_{geom} were calculated and the following relationships established

$$\frac{k_{0.42}}{2S_{geom}} = C.$$

It was demonstrated that in all cases C exceeds unity, increasing

with an increase in τ and for large optical densities reaching values

of about 7 − 8. The correlation between the ratio C and $k_{0.42}$ is shown

in Fig. 2. We should note the large value of the coefficient of

correlation between C and $k_{0.42}$ close to 0.8 and the circumstance that

practically all measured coefficients of attenuation were greater

than calculated. The rather large divergence of points in Fig. 2 may

not be completely explained by errors in microphysical and spectral

measurements. Apparently it is brought about by the specific nature

of the conditions under which the fog was formed (droplets of small

dimension, strong intermixing of fog, presence of density fluctuations,

located on the optical installations).

The magnitude of discrepancy between optical and microphysical

data depends on the size of the diffusion particles. If from Fig. 2,

which gives a summary of data for fog with various d_2, one selects

data for certain intervals of d_2 then the results of selection indicat

an explicit dependence of the magnitude of discrepancy on d_2, this

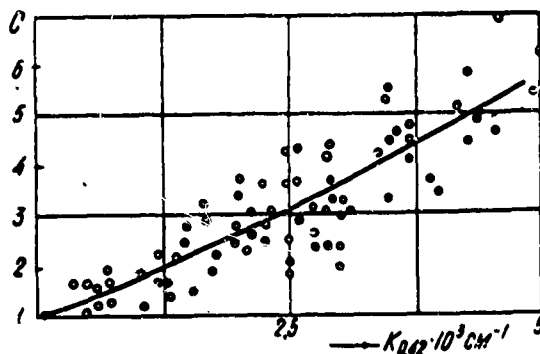quantity becoming greater with an increase in d_2.

Fig. 2.

Analysis of the discrepancy between the measured and calculated

coefficients of attenuation for visible light noted in several

other works (e.g. [15]) indicate that these discrepancies may not be

explained by the presence of an uncontrolled fine-droplet fraction

or the effect of multiple scattering. The causes of such a discrepanc

require the establishment of a separate special study.

Since measurements of the attenuation factor k_λ in the infrared

spectral range were accompanied by a simultaneous determination of

the microstructure of artificial fogs and the coefficient $k_{0.42}$, it

becomes of interest to find the spectral path of the ratio $\dfrac{k_\lambda}{k_{0.42}} = \varepsilon$,

established with respect to average data of various experiments.

Figure 3 shows value of the ratio $k_\lambda/k_{0.42}$ obtained for various λ. The

continuous curve corresponds to data obtained in fogs with a mean-

square diameter d_2 equal to 14 μ; the broken line, to $d_2 = 20$ μ. As

can be seen from Fig. 3 an artificial fog with $d_2 = 14$ μ in the range

of 10 μ has a unique "transmission window" which with an increase in

droplet size shifts in the direction of larger wavelengths but does not altogether disappear. The existence of such a window for real clouds and fog has been demonstrated in [3, 16].

Thanks to great variation in microstructure in the artificial fog studied it was possible to trace the change in ε as a function of mean-square diameter. In Fig. 4 the circles indicate experimental data, the continuous curves, data by Levin [8] calculated according to the formula $\frac{S_{opt}}{2S_{geom}}$, where S_{geom} is the geometric cross section of the droplets in units of volume, S_{opt}, the optical value of the droplet having the form

$$S_{opt} = \int_0^\infty \frac{\pi d^2}{4} K(\rho) N f(d) Dd,$$

where k(ρ) is the Hauton-Chalker function, N the calculated droplet concentration, f(d) the function of droplet distribution with respect to size.

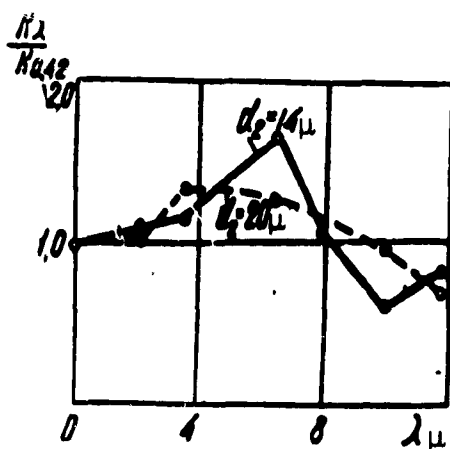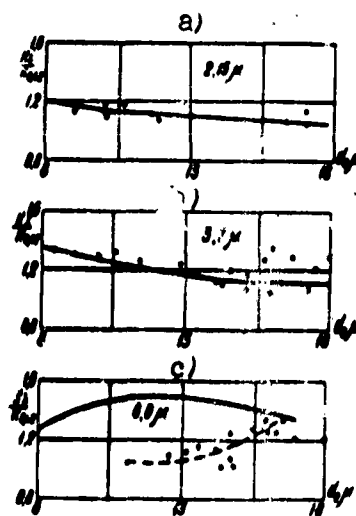.Fig. 3.   Fig. 4.

It rhould be noted that the data calculated by Levin, which was used fcr comparison with the experimental values of $k_\lambda/k_{0.42}$ obtained by us, refer to a value of the actual refractive index m = 1.33. In this connection an agreement of calculated and experimental data for

wavelengths 2.15 and 3.7 μ is understandable (Fig. 4a and 4b; the value
of m in this case actually differs little from 1.33) as are significant
discrepancies in data for the wavelength 8.0 μ. In the latter case
the theoretical data used may not pretend to be a correct description
of the phenomena due to the neglect of the complexity of the refractiv
index for this wavelength. The results of calculations of the atten-
uation coefficients in the infrared spectral range due to the
complexity of m and the microstructures of the aerosol and their
comparison with experimental data obtained by us will be considered
in the next report.

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